

# The D0 Dimuon Charge Asymmetry and Baryon Asymmetry of the Universe

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## Abstract

The D0 collaboration has reported a  $3.2\sigma$  deviation from the standard model (SM) prediction in the like-sign dimuon charge asymmetry. New physics beyond the SM in  $B_s - \bar{B}_s$  mixing is needed to explain the data. In this paper, we investigate the possible extension of the SM with one generation color-triplet charged scalar as well as three generation Majorana fermions. We study the implications of the model on the D0's dimuon charge asymmetry as well as matter anti-matter asymmetry of the Universe.

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## I. INTRODUCTION

The cosmological matter-antimatter asymmetry is one of the most striking mysteries in the Universe. The five-year observations of the WMAP collaboration precisely measured the ratio of baryon number to photon number densities as [1]

$$\eta_B = \frac{n_B}{n_\gamma} = (6.225 \pm 0.170) \times 10^{-10} . \quad (1)$$

According to Sakharov's suggestion [2], to dynamically generate the matter-antimatter asymmetry of the Universe, three conditions must be satisfied, which are the violation of baryon number conservation, the violation of C and CP, and the deviation from thermal equilibrium. In the standard model (SM), C parity is maximally violated and the phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix is the sole source of the CP violation. However, this CP violation effect, which has been precisely measured in hadronic physics, is too small to be used to accommodate the baryon asymmetry of the Universe. Such that, investigating the new origin of CP violation is a subject with great significance.

More recently, the D0 collaboration [3], with  $6.1\text{fb}^{-1}$  of data, has reported a measurement of the like-sign dimuon charge asymmetry in semi-leptonic decay of  $b$  hadrons,

$$A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3} , \quad (2)$$

where  $N_b^{++}(N_b^{--})$  is the number of events with  $b(\bar{b})$  hadrons decaying semileptonically into  $\mu^+X(\mu^-X)$ . This result, with the first error being statistical and the second systematic, is  $3.2\sigma$  deviation from the SM prediction of  $-0.2 \times 10^{-3}$  [4].  $A_{sl}^b$  was also measured by the CDF collaboration [5], which has  $A_{sl}^b = (8.0 \pm 9.0 \pm 6.8) \times 10^{-3}$ , using  $1.6\text{fb}^{-1}$  of data. This result is positive but still compatible with the D0 measurement at  $1.5\sigma$  level because its uncertainties are 4 times larger than those of D0. Combining in quadrature these two results, one has  $A_{sl}^b \approx -(8.5 \pm 2.8) \times 10^{-3}$  [6] which is still  $3\sigma$  away from the SM value. If confirmed, it will be an evidence of new physics beyond the SM. There have already been some models [6–8] attempting to explain the data.

The D0 collaboration's result is the first laboratory evidence for significant matter-antimatter asymmetry. We suspect there should be some connection between the baryon asymmetry of the Universe and this anomaly. In this paper, we consider the possible extension of the SM with one color-triplet charged scalar and three Majorana fermion singlets.

In this model, there are tree level processes leading to dimension six effective operators, like  $\mathcal{O}(1/M_\varphi^2)\bar{b}s\bar{c}c$ , which may contribute to  $B_s - \bar{B}_s$  mixing and thus the like-sign dimuon charge asymmetry can be explained. Besides, the out of equilibrium decay of the neutral fermion may produce  $B - L$  asymmetry. This asymmetry may be converted to the baryon asymmetry of the universe via sphaleron process [12], which violates  $B + L$  but keeps  $B - L$  conservation.

The paper is organized as follows: In section II, we present our model. Section III is devoted to investigating the like-sign dimuon charge asymmetry. We study baryogenesis in section IV. Conclusions and remarks are presented in section V.

## II. THE MODEL

To reproduce the large anomalous like-sign dimuon charge asymmetry observed by D0 and to explain the matter-antimatter asymmetry of the Universe, new physics beyond the SM is needed. In this section, we consider the possible extension of the SM with one charged scalar  $\varphi$  and three fermion singlets  $\chi$ , whose representation in  $SU(3)_C \times SU(2)_L \times U(1)_Y$  gauge group are  $\varphi : (3, 1, -1/3)$  and  $\chi : (1, 1, 0)$ , respectively. For simplification,  $Z_3$  discrete flavor symmetry is introduced and the presentations of fields on  $Z_3$  are listed in table I. The newly introduced lagrangian can be written as

$$\begin{aligned} \mathcal{L}_{\text{New}} = & |(\partial_\mu + i\lambda_a G_\mu^a + iY B_\mu)\varphi|^2 + \bar{\chi}i\not{\partial}\chi - \frac{1}{2}M\bar{\chi}\chi - \frac{1}{2}M_S\varphi^\dagger\varphi - \frac{1}{4}\lambda_1(\varphi^\dagger\varphi)(H^\dagger H) \\ & - \zeta\bar{\chi}\varphi D_R - \lambda U_R^T \bar{\varphi} D_R + \text{h.c.} , \end{aligned} \quad (3)$$

where  $\zeta$  and  $\lambda$  are Yukawa coupling matrices,  $H$  is the SM Higgs boson,  $U_R$  and  $D_R$  represent the second or third generation right-handed up- and down-type quarks. Assuming  $\varphi$  has baryon number  $2/3$ , the interaction,  $\bar{\chi}\varphi d_R$ , violates baryon number by 1 unit.

fields	$Z_3$
$Q_L, u_R, d_R$	1
$\varphi, \chi, s_R, c_R, t_R, b_R$	$\omega$
$H,$	$\omega^2$

TABLE I: Representations of fields on  $Z_3$  flavor symmetry.

Note that  $Z_3$  symmetry is explicitly broken down by the Yukawa interactions containing the first generation right-handed quarks and the mass term of  $\chi$ . We may introduce another Higgs doublet, whose representation under  $Z_3$  is 1, to generate masses for the first generation up- or down-type quarks, and introduce one Higgs singlet, whose representation under  $Z_3$  is  $\omega$ , to generate masses for  $\chi$ . Such that  $Z_3$  symmetry can be recovered. Due to the existence of  $Z_3$  symmetry,  $\varphi$  and  $\chi$  do not couple to the first generation of quarks. As a result, we need not to worry about constraints from proton stability,  $K_0 - \bar{K}_0$  mixing or  $D_0 - \bar{D}_0$  mixing. Notice that  $\varphi$  is similar to the super-partner of  $d_R$  and  $\lambda u_R^T \varphi d_R$  is similar to  $R$ -parity violating interactions in supersymmetry. The experimental lower bound for the mass of  $\varphi$  should be consistent with that of squarks. Integrating out heavy degrees of freedom, we can derive an effective operator that contributes to  $b \rightarrow s\gamma$ . The inclusive decay width for this process can be written as

$$\Gamma(b \rightarrow s\gamma) = \frac{e^2 m_b^5}{16\pi} (|\mathcal{F}|^2 + |\mathcal{Q}|^2) , \quad (4)$$

where  $\mathcal{Q}$  is the contribution of SM penguin diagram and

$$\mathcal{F} = \frac{1}{24\pi^2 M_\varphi^2} \lambda_{is}^* \lambda_{ib} \left[ \frac{2}{3(1-x)} + \frac{1+x-4x^2}{2(1-x)^3} + \frac{2x-3x^2}{(1-x)^4} \ln x \right] , \quad (5)$$

comes from the new interaction in our model, with  $x = m_i^2/M_\varphi^2$ . Assuming  $\lambda_{is}^* \lambda_{ib} \sim 0.1$  and  $M_\varphi = 500\text{GeV}$ , we get the predication for the branching ratio of  $b \rightarrow s\gamma$ :  $\text{BR}(b \rightarrow s\gamma) = 3.53 \times 10^{-4}$ , which is consistent with its present experimental value,  $(3.55 \pm 0.24_{-0.10}^{+0.09}) \times 10^{-4}$ , predicted by the Heavy Flavor Average Group (HFAG) [9].

### III. $B_s - \bar{B}_s$ MIXING

Notice that,  $A_{sl}^b$ , appearing in Eq. (2), is blind as to which flavors of  $B$  meson produced the two muon, it places a constraint on the semi-leptonic CP asymmetries of both  $B_d$  and  $B_s$  mesons, which we will call  $a_{sl}^d$  and  $a_{sl}^s$ , respectively. The relation between  $A_{sl}^b$  and  $a_{sl}^{s,d}$  is given by

$$A_{sl}^b = (0.506 \pm 0.043) a_{sl}^d + (0.494 \pm 0.043) a_{sl}^s . \quad (6)$$

Taking into account the current experimental value of  $a_{sl}^d = -0.0047 \pm 0.0046$  [10], one obtains  $a_{sl}^s = -0.0146 \pm 0.0075$ , which is in agreement with D0's direct measurement of

$a_{sl}^s = -0.0017 \pm 0.0094$  [3], albeit with large uncertainties. We may combine all these results to obtain an average value  $a_{sl}^s \approx -(12.7 \pm 5.0) \times 10^{-3}$ .

Theoretically, there are two amplitudes characterizing mixing in  $B_s$  system: the off-diagonal element of the mass matrix  $M_{12}^s$  and the off-diagonal element of the decay matrix  $\Gamma_{12}^s$ . The violation of CP is caused by the non-zero value of the phase:  $\phi_s = \arg(-M_{12}^s/\Gamma_{12}^s)$ . In terms of these parameters, to a very good approximation,  $a_{sl}^s$  is given by [13]

$$a_{sl}^s = \frac{|\Gamma_{12}^s|}{|M_{12}^s|} \sin \phi_s = \frac{\Delta \Gamma_s}{\Delta M_s} \tan \phi_s, \quad (7)$$

where  $\Delta M_s = 2M_{12}^s$  and  $\Delta \Gamma_s = 2|\Gamma_{12}^s| \cos \phi_s$ . Notice that the SM prediction for  $\Delta M_s$  agrees with data very well, while both  $\Delta \Gamma_s$  and  $\phi_s$  differ from the experimental data by about  $1.5\sigma$  and  $3\sigma$ , respectively. It is natural to attribute D0's result to big corrections to  $\Gamma_{12}$  and  $\phi_s$  from new physics.

In our model, there are tree level contributions to the dimension six effective operator  $\mathcal{O}(1/M_\varphi^2)\bar{b}s\bar{c}c$ , which contributes to  $\Gamma_{12}$  for  $B_s - \bar{B}_s$  mixing. Integrating out  $\varphi$  at the tree level, we have

$$\delta \mathcal{L} = \frac{\lambda_{ik}\lambda_{jl}^*}{2M_\varphi^2} (\bar{u}_i^\alpha \gamma^\mu P_R u_j^\alpha \bar{d}_k^\beta \gamma_\mu P_R d_l^\beta - \bar{u}_i^\alpha \gamma^\mu P_R u_j^\beta \bar{d}_k^\beta \gamma_\mu P_R d_l^\alpha), \quad (8)$$

where  $i, j, k, l$  are generation indices and  $\alpha, \beta$  are color indices. Starting with these four quark interactions, one can derive the expression of  $\Gamma_{12}^s$ :

$$\Gamma_{12}^\lambda \approx \frac{m_b^2}{128\pi m_B} \frac{(\lambda_{22}\lambda_{23}^*)^2}{M_\varphi^4} \langle Q_s \rangle, \quad (9)$$

where  $\langle Q_s \rangle = \langle B_s | \bar{s}_\alpha \gamma_\mu P_R b_\beta \bar{s}_\beta \gamma_\mu P_R b_\alpha | \bar{B}_s \rangle = -(5/12)f_{B_s}^2 B_{B_s}^s m_{B_s}^2$ .  $B_{B_s}^s$  is the bag parameter and we take it to be equal to one.

There are also contributions to the off-diagonal elements,  $M_{12}^s$ , of the mass matrix of the  $B_s - \bar{B}_s$  system due to the box diagram. Using vacuum insertion approximation, we have

$$M_{12}^\lambda = -\frac{1}{192\pi^2 M_\varphi^2} (\lambda_{3\alpha}^\dagger \lambda_{\alpha 2} \lambda_{3\beta}^\dagger \lambda_{\beta 2}) f_B^2 M_B B_b \exp[i(\xi_b - \xi_q - \xi_{B_q})] \mathcal{F}^*(x_\alpha, x_\beta), \quad (10)$$

with [13]

$$\begin{aligned} \mathcal{F}(x_\alpha, x_\beta) = & \frac{1}{(1-x_\alpha)(1-x_\beta)} \left( \frac{7x_\alpha x_\beta}{4} - 1 \right) + \frac{x_\alpha^2 \ln x_\alpha}{(x_\alpha - x_\beta)(1-x_\alpha^2)} \left( 1 - 2x_\beta + \frac{x_\alpha x_\beta}{4} \right) \\ & + \frac{x_\beta^2 \ln x_\beta}{(x_\alpha - x_\beta)(1-x_\beta)} \left( 1 - 2x_\alpha + \frac{x_\alpha x_\beta}{4} \right), \end{aligned}$$

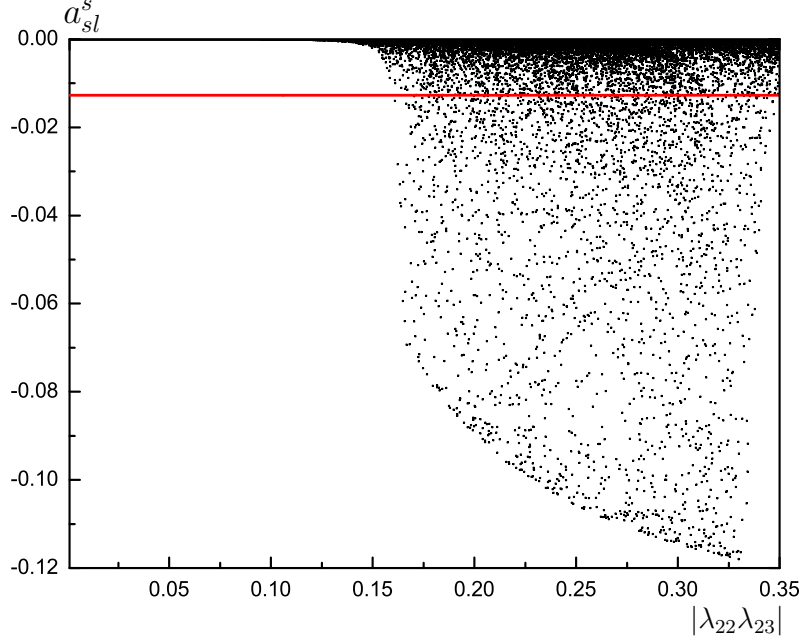


FIG. 1:  $a_{sl}^s$  as function of  $|\lambda_{22}\lambda_{32}|$  with  $M_\varphi$  being random parameter in the range  $[300, 600]$  (GeV). The horizontal line represents the central value of  $a_{sl}^s$  measured by  $D0$ .

where  $x_{\alpha,\beta} = m_{\alpha,\beta}^2/M_\varphi^2$  ( $\alpha, \beta = c, t$ ). In deriving Eq. (10), we have ignored the contributions from the  $\zeta\chi\varphi d_R$  term by assuming  $\mathcal{O}(\zeta) \ll \mathcal{O}(\lambda)$ .

Taking into account contributions from new physics, the final expressions for  $M_{12}^s$  and  $\Gamma_{12}^s$  can be written as

$$M_{12}^s = M_{12}^{\text{SM}} + M_{12}^\lambda ; \quad \Gamma_{12}^s = \Gamma_{12}^{\text{SM}} + \Gamma_{12}^\lambda , \quad (11)$$

where the formulae for  $M_{12}^{\text{SM}}$  and  $\Gamma_{12}^{\text{SM}}$  are given by [11]

$$M_{12}^{\text{SM}} = -\frac{G_F^2 M_W^2 \eta_B m_{B_q} B_{B_q} f_{B_q}^2 (V_{tq}^* V_{tb})^2 S_0 \left( \frac{m_t^2}{M_W^2} \right)}{12\pi^2} , \quad (12)$$

$$\Gamma_{12}^{\text{SM}} = \frac{G_F^2 m_b^2 \eta'_B m_{B_q} B_{B_q} f_{B_q}^2}{8\pi} \left[ (V_{tq}^* V_{tb})^2 + V_{tq}^* V_{tb} V_{cq}^* V_{cb} \mathcal{O} \left( \frac{m_c^2}{m_b^2} \right) \right] . \quad (13)$$

Since the couplings are in general complex, we can derive arbitrary phase  $\phi_s$  in general. Before giving some numerical analysis, let's assume that the Yukawa coupling constant  $\lambda$  is real, and the operator  $\mathcal{O}(1/M_\varphi^2)\bar{b}s\bar{c}c$  dominates contributions to  $\Gamma_{12}^\lambda$  and  $M_{12}^\lambda$ . In this case,  $\phi_s$  as well as  $a_{sl}^s$  will be functions of  $|\lambda_{22}\lambda_{23}|$  and  $M_\varphi$ . We plot in Fig. 1,  $a_{sl}^s$  as function of  $|\lambda_{22}\lambda_{23}|$  with  $M_\varphi$  being a random parameter in the range  $[300, 600]$  (GeV). The horizontal line represents the central value of  $a_{sl}^s$  measured by  $D0$ . It is clear that, to fit the data,

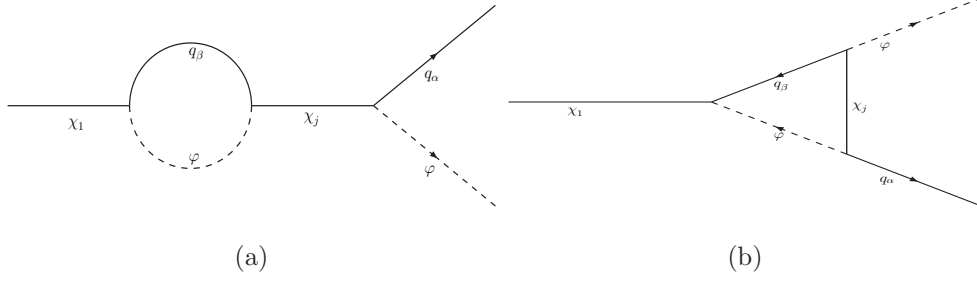


FIG. 2: The decays of  $\chi$  at one loop level for generating  $B - L$  asymmetry.

$|\lambda_{22}\lambda_{23}|$  should be larger than 0.17. Of course,  $|\lambda_{22}\lambda_{23}^*|$  can be much smaller in the case  $\lambda$  being complex.

#### IV. BARYOGENESIS

As noticed in the last section, the D0's like-sign dimuon charge asymmetry can be explained by introducing a color-triplet scalar  $\varphi$ . As a byproduct, this may induce baryon number violating operators like  $\zeta \bar{\chi} \varphi d_R$ , which is just what we need to reproduce the baryon asymmetry of the universe. We assume  $\chi$  is thermally produced in the early universe. Its out of equilibrium decay, as shown in Fig 2, may violate the  $B - L$  symmetry. The expression for the CP asymmetry  $\varepsilon$  in the decay of  $\chi$ , which is similar to that in the decay of heavy Majorana neutrinos in the Type-I seesaw mechanism [14], can be written as

$$\varepsilon = \frac{\Gamma(\chi \rightarrow \varphi d_R) - \Gamma(\chi \rightarrow \bar{\varphi} \bar{d}_R)}{\Gamma(\chi \rightarrow \varphi d_R) + \Gamma(\chi \rightarrow \bar{\varphi} \bar{d}_R)} = \frac{1}{8\pi} \sum_i \frac{\text{Im}[(\zeta \zeta^\dagger)_{i1}^2]}{[\zeta \zeta^\dagger]_{11}} f\left(\frac{M_{\chi_i}^2}{M_{\chi_1}^2}\right), \quad (14)$$

where  $f(x)$  is given by

$$f(x) = \sqrt{x} \left[ \frac{x-2}{x-1} - (1+x) \ln \left( \frac{1+x}{x} \right) \right]. \quad (15)$$

After the evolution of Boltzmann equations governing the baryon number density, we derive the  $B - L$  asymmetry stored in right-handed quarks. Because all the quarks are in thermal equilibrium, this asymmetry may be converted to left-handed quarks through the left-right equilibrium [15], which can be understood as follows. Let us define the chemical potential associated with the  $q_R$  field as  $\mu_{q_R} = \mu_0 + \mu_{BL}$ , where  $\mu_{BL}$  is the chemical potential contributing to  $B - L$  asymmetry and  $\mu_0$  is independent of  $B - L$ . Hence at equilibrium we have the chemical potential associated with  $Q_L$  given by  $\mu_{Q_L} = \mu_0 + \mu_{BL} + \mu_H$ . Thus we see that the same chemical potential is associated with  $Q_L$  as that of  $q_R$ . Finally, the  $B - L$

asymmetry is converted to the baryon asymmetry of the Universe through the sphaleron process, which violates  $B + L$  symmetry but keeps  $B - L$  conservation. Then the final baryon asymmetry can be given as [16]

$$\eta_B \approx \frac{28}{79} \frac{0.3\varepsilon}{g_* K (\ln K)^{0.6}}, \quad (16)$$

with

$$K = \frac{\Gamma_D}{2H}(T = M_\chi) \approx \frac{3(\zeta\zeta^\dagger)_{11} M_{pl}}{32\pi\sqrt{g^*} M_\chi}, \quad (17)$$

which measures the effectiveness of decays at the crucial epoch ( $T \sim m_\chi$ ) when  $\chi$  must decrease in number if they are to stay in equilibrium. Here,  $M_{pl} = 1.2 \times 10^{19}$  GeV is the Planck mass and  $g_*$  is effective degrees of freedom, at the temperature where  $\chi$  decouples. In deriving Eq. (16), we have assumed that the factor  $K$  is greater than 1, but not too large. If  $K \ll 1$ ,  $\eta_B \approx 28\varepsilon/79g_*$ . For instance, inputting  $M_{\chi 1} = 0.1M_{\chi 2} = 10^7$  GeV,  $K=50$ ,  $\sum_i(\zeta\zeta^\dagger)_{i1} \sim 1.3 \times 10^{-5}$  and maximal CP-phase, we derive the sample predication:  $\varepsilon = 7 \times 10^{-5}$ . In consequence, we deduce  $\eta_B \sim 10^{-10}$ , as desired.

## V. CONCLUDING REMARKS

We have extended the SM by introducing one color-triplet charged scalar,  $\varphi$ , and three Majorana fermions,  $\chi$ . We have shown that the dimuon charge asymmetry, reported by the D0 collaboration, can be explained by the Yukawa interaction, like  $\lambda U_R^T \varphi D_R$ . Besides, the matter-antimatter asymmetry of the Universe can be realized by the out of equilibrium decays of  $\chi$ . Notice that, the mass of  $\varphi$  can be several hundred GeV. It can be produced and detected at the Large Hadron Collider.

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